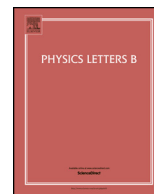


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www.elsevier.com/locate/physletbCharged charmonium-like $Z^+(4430)$ from rescattering in conventional B decaysP. Pakhlov^{a,b}, T. Uglov^{b,a,*}^a Moscow Institute of Physics and Technology, Moscow Region, Russia^b Moscow Engineering Physics Institute, Moscow, Russia

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ABSTRACT

In a previous paper we suggested an explanation for the peak designated as $Z(4430)^+$ in the $\psi'\pi^+$ mass spectrum, observed by Belle in $\bar{B} \rightarrow \psi'\pi^+K$ decays, as an effect of $\bar{D}^{*0}D^+ \rightarrow \psi'\pi^+$ rescattering in the decays $\bar{B} \rightarrow D_s'^-D$, where the $D_s'^-$ is an as-yet unobserved radial excitation of the pseudoscalar ground state D_s^- -meson. In this paper, we demonstrate that this hypothesis provides an explanation of the double Z^+ -like peaking structures, which were studied by LHCb with much higher statistics. While according to our hypothesis, the origin of the peaking structures is due to the kinematical reflection of conventional resonances in the unobserved intermediate state, the amplitude of the $Z(4430)^+$ peak carries a Breit–Wigner-like complex phase, arising from the intermediate $D_s'^-$ resonance. Thus, our hypothesis is entirely consistent with the recent LHCb measurement of the resonant-like amplitude behavior of the $Z(4430)^+$. We perform a toy fit to the LHCb data, which illustrates that our approach is also consistent with all the observed structure in the LHCb $M(\psi'\pi^+)$ spectrum. We suggest a critical test of our hypothesis that can be performed experimentally.

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Many XYZ states above open charm threshold, and decaying into charmonium and light hadron(s) have been observed within the past decade. Their conventional interpretation as charmonium states remains controversial as their properties, especially their large decay rates into final states without open charm, do not easily match the levels of heretofore unobserved charmonia. Various exotic explanations, such as tetraquarks, molecular states, charmonium hybrids and hadrocharmonium are also not fully embraced by the physics community, as they cannot describe the variety of observed states, and all their measured properties, within a single self-consistent approach.

The first charmonium-like state, the $Z(4430)^+$, which is entirely inconsistent with a simple charmonium interpretation, was observed by Belle [1,2] in 2007 as a peak in the $\psi'\pi^+$ mass near $M \sim 4430$ MeV in B decays. Interpreted as a real resonance containing a $c\bar{c}$ pair, its minimal quark content given its non-zero charge ($u\bar{d}c\bar{c}$), is necessarily exotic. The existence of the $Z(4430)^+$ was cast into doubt by BaBar [3], but the recent $Z(4430)^+$ observation by LHCb [4] unambiguously (with significance $\sim 14\sigma$) supports Belle's claim.

Among the exotic explanations of the $Z(4430)^+$, the most popular are the tetraquark [5], hadrocharmonium [6] and DD^{**} molecules [7]. There are also non-resonant interpretations such as the “cusp effect” [8], rescattering via the chain $\bar{B} \rightarrow D^{*-}D_1(2420)K \rightarrow \psi'\pi^+K$ [9], and the initial single pion emission mechanism [10]. In our previous paper [11], we suggested another possible explanation of the $Z(4430)^+$ peak, resulting from $\bar{D}^{*0}D^+ \rightarrow \psi'\pi^+$ rescattering in the decays $\bar{B} \rightarrow D_s'^-D^+$. Although this decay has not yet been observed and even the $D_s'^-$ -meson not yet discovered, the branching fraction for the decay $\bar{B} \rightarrow D_s'^-D^+$ is expected to be large, similar to that observed for $B^+ \rightarrow D_s^{*-}D^0$ [13], while the mass of the $D_s'^-$ is predicted in the range (2600–2650) MeV – which corresponds to the range that provides a $Z(4430)^+$ peak value consistent with the extant experimental data.

If our *ad hoc* hypothesis is correct, the origin of the $Z(4430)^+$ peaking structure is caused by the presence of a conventional resonance (the $D_s'^-$ meson) in the hidden intermediate state. However, our explanation also implies an interesting underlying phenomenon: namely, a non-vanishing rescattering amplitude over a wide range of $M(\bar{D}^{*0}D^+)$. In this Letter, we demonstrate that our approach is fully consistent with all the experimental data, including the recent $Z(4430)^+$ phase study by LHCb, as the $Z(4430)^+$ phase would then arise from the Breit–Wigner $D_s'^-$ amplitude.

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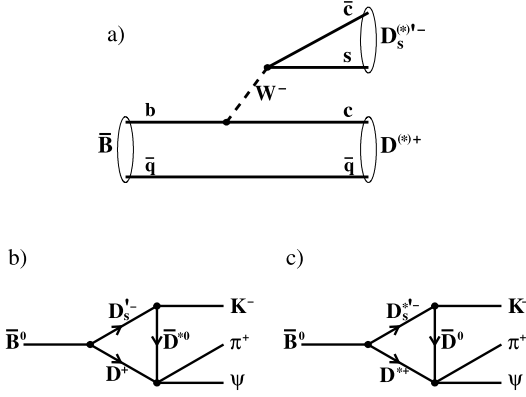


Fig. 1. a) Feynman diagram for B decay into radially excited D_s^- mesons. Rescattering processes $(\bar{D}D)^{*+} \rightarrow \psi'\pi^+$, represented by triangle diagrams: a) for the chain 1 and b) for the chain 2.

We show that other structures that are evident in the LHCb $\psi'\pi^+$ spectrum can be attributed to similar effects. We also suggest here a critical test of our hypothesis that can be performed by Belle, BaBar and LHCb.

First, we note that in our previous paper [11] we have predicted the quantum numbers of the $Z(4430)^+$ to be $J^P = 1^+$ based on the simple argument that the $\bar{D}^{*0}D^+ \rightarrow \psi'\pi^+$ rescattering should be dominated by S -waves in both the colliding $\bar{D}^{*0}D^+$ and also the produced $\psi'\pi^+$ systems. This prediction was confirmed by subsequent Belle [12] and LHCb [4] measurements. We also predicted the presence of other structures in the $\psi'\pi^+$ spectrum, in particular near $M \sim 4200$ MeV, which arise from another $\bar{B} \rightarrow D_s^{*-}D^+$ decay chain. Such a broad peak at $M = 4239$ MeV is, indeed, observed in the LHCb data, and has been interpreted as another Z^+ resonance.

We reiterate the main points of our hypothesis. As in our previous paper [11] we consider B decays governed by the tree diagrams shown in Fig. 1 a). In these decays the W^- is directly coupled to the radial excitations of the D_s^- and D_s^{*-} -mesons (the $D_s'^-$ and D_s^{*-}) in a similar way as to their ground states. One of such mode, $B^- \rightarrow D_{s1}^*(2700)^-D^0$, was observed by Belle with a relatively large branching fraction $\mathcal{B}(B^- \rightarrow D_{s1}^*(2700)^-D^0) \times \mathcal{B}(D_{s1}^*(2700)^- \rightarrow \bar{D}^0K) \sim 10^{-3}$ [13]. The measured quantum numbers of the $D_{s1}^*(2700)^-$ ($J^P = 1^-$) suggest the interpretation of this state as the D_s^{*-} meson. Other channels and even the $D_s'^-$ have not, thus far, been explicitly searched for experimentally. However, the inclusive $B \rightarrow D^{(*)}\bar{D}^{(*)}K$ branching fractions are large: they vary from 0.1 to 1% [15]. It is natural to assume that they should be saturated by two-body modes with intermediate radial D_s^- and D_s^{*-} excitations, since the known contribution of orbital D_s^- excitations to these final states is small [15].

The $D_s'^-$ -meson is expected to decay mostly to the D^*K final state, as the decay $D_s'^- \rightarrow DK$ is forbidden by parity conservation, while the D_s^{*-} decays to both DK and D^*K [15]. Therefore the B decays under consideration hadronize into $D^{(*)}\bar{D}^{(*)}K$ final states. We note that two charmed mesons are produced spatially at the same point and fly apart relatively slowly with $v/c \approx 0.3-0.5$. Therefore one can expect the non-vanishing rescattering of two charmed mesons into charmonium plus a light meson. Considering the S -wave rescattering as a recombination of the charm quark from one charmed meson and the charm antiquark from the other into charmonium, with the simultaneous merging of a light quark-antiquark pair into a light meson, we conclude that only $D\bar{D}^* + c.c.$ states can result in rescattering into $\psi'\pi^+$ or $J/\psi\pi^+$. Other $(D\bar{D}$ and $D^*\bar{D}^*)$ can rescatter to other charmonia and/or other light mesons. The rescattering amplitude can be determined

by the overlap integral of two products of wave functions with the same quark content, taking into account color suppression. We do not attempt such calculations, which can only be done by invoking a model for light and heavy mesons and charmonium wave functions, but simply assume that this amplitude is small but not vanishing, and does not change dramatically within the range of interest ($M_D + M_{D^*} < M_{(\bar{D}D)^{*+}} \lesssim 4.8$ GeV).

Of the decay chains discussed above, only two can contribute to the $\psi'\pi^+K$ final state:

$$\bar{B} \rightarrow D_s'^-D^+, \text{ followed by } D_s'^- \rightarrow \bar{D}^{*0}K^-, \quad (1)$$

and

$$\bar{B} \rightarrow D_s^{*-}D^{*+}, \text{ followed by } D_s^{*-} \rightarrow \bar{D}^0K^-. \quad (2)$$

They corresponds to the triangle diagrams in Fig. 1 b) and c) respectively. The decay $\bar{B} \rightarrow D_s'^-D^+$ which could otherwise contribute to this process, has parity opposite Z^+K^- and is therefore not considered. We note that while parity is not conserved in B decays, the rescattering process is mediated by the strong interaction and requires parity conservation.

We introduce a common notation, $(\bar{D}D)^{*+}$, to refer to both $\bar{D}^{*0}D^+$ and $D^{*+}\bar{D}^0$ systems in the reactions (1) and (2), respectively, and designate as Z^+ a pseudoparticle with $J^P = 1^+$ formed by the $(\bar{D}D)^{*+}$ combination before its subsequent decay to $\psi'\pi^+$.

As in our previous paper, we calculate the amplitude of interest in the on-shell approximation of the triangle diagrams (Fig. 1), taking into account the $D_s^{(*)-}$ Breit-Wigner amplitude. We also include the D^* spin rotation amplitudes, which provide the proper D^* helicity in the Z^+ system, corresponding to S -wave formation of the Z^+ . Depending on the $D_s^{(*)-}$ decay angle different values of $D_s^{(*)-}$ mass within the Breit-Wigner distribution can yield the same $(\bar{D}D)^{*+}$ mass. Thus, the total amplitude \mathcal{A}_{Z^+} should be calculated as a superposition of all allowed values of $M(D_s^{(*)-})$, accounting for the variation in phase with mass. Unlike our previous paper, here we therefore integrate the entire allowed kinematic region, explicitly including the variation in phase. This procedure is more rigorous, and the Z^+ shape is also slightly changed, relative to our previous calculations. The full decay amplitude has the following form in the helicity formalism:

$$\mathcal{A}(M_{Z^+} \equiv M_{(\bar{D}D)^{*+}}) = \sum_{\lambda} \int \mathcal{A}_{BW}(M_{D_s^{(*)-}}) D_{0,\lambda}^J(\theta_{\text{dec}}) D_{\lambda,0}^1(\theta_{\text{rot}}) D_{0,0}^1(\theta_{\text{form}}) dM_{D_s^{(*)-}}, \quad (3)$$

where J is the $D_s^{(*)-}$ spin; θ_{dec} is the decay angle of the $D_s^{(*)-}$ (the angle between the \bar{B} and \bar{D}^{*0} in the $D_s^{(*)-}$ rest frame); θ_{rot} is the rotation angle of the \bar{D}^{*0} spin from the $D_s^{(*)-}$ frame for the reaction (1) or the \bar{B} frame for the reaction (2) to the Z^+ frame; θ_{form} is the formation angle of Z^+ , i.e. the angle between the \bar{B} and D^* in the Z^+ rest frame. The first Wigner D -function is responsible for the proper angular distribution of the $D_s^{(*)-}$ decay (in the case considered in (2), only the zero helicity projection is considered). The second function, $D_{0,\lambda}^1(\theta_{\text{rot}})$, describes the D^* spin rotation from the frame where it is produced to the frame where it is absorbed. Finally, the $D_{0,0}^1(\theta_{\text{form}})$ corresponds to the proper formation of the spin-1 Z^+ pseudostate from the vector (D^*) and the pseudoscalar (D). Two variables, $M_{D_s^{(*)-}}$ and θ_{dec} , fully describe the three-body kinematics, thus $M_{(\bar{D}D)^{*+}}$, θ_{rot} and θ_{form} are functions of these two variables.

We have performed the calculation of Equation (3) numerically using Monte Carlo simulations. We first generate the $\bar{B} \rightarrow D_s^{(*)-}D^{(*)}$ decay kinematics. The mass and width of the $D_s^{(*)-}$ are

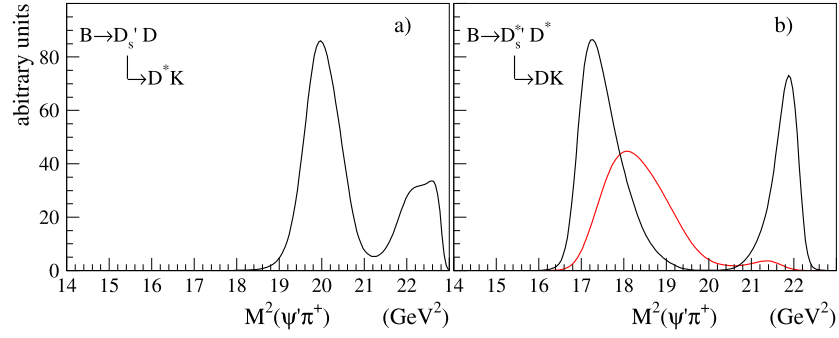


Fig. 2. The $M^2_{\psi'\pi^+}$ spectrum in the decay $B \rightarrow D_s^{(*)'} D^+$, followed by rescattering $(\bar{D}D)^{*+} \rightarrow \psi'\pi^+$, calculated according to Equation (3). a) and b) correspond to the chains (1) and (2). The black and red curves correspond to the lineshapes for $\lambda_{D^*} = 0$ and $\lambda_{D^*} = \pm 1$, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

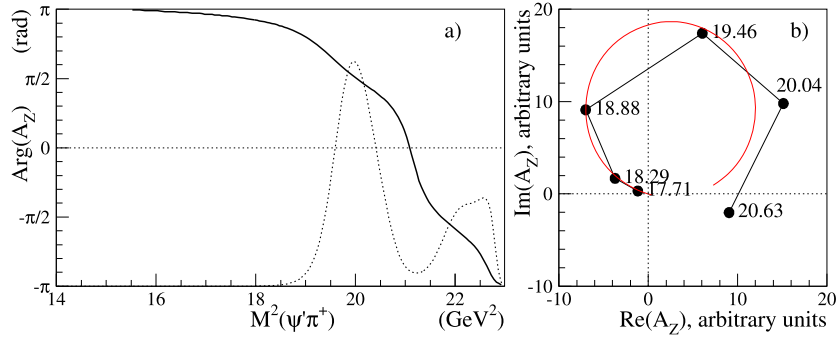


Fig. 3. a) The phase of $\mathcal{A}(M_{Z^+})$ in the decay $B \rightarrow D_s^{(*)'} D^+ \rightarrow \bar{D}^0 K^- D^+$, followed by rescattering $\bar{D}^0 D^+ \rightarrow \psi'\pi^+$, calculated according to Equation (3) as a function of M_{Z^+} ; the dashed curve represents the process lineshape ($\propto |\mathcal{A}(M_{Z^+})|^2$). b) The Argand diagram for rescattering contribution around the $Z(4430)^+$ peak.

fixed to the PDG values ($M = 2.709$ MeV, $\Gamma = 0.112$ MeV [15]); the $D_s^{(*)'}$ parameters are fixed to $M = 2610$ MeV and $\Gamma = 100$ MeV as in our previous paper [11] (the expected $2S^1-2S^3$ splitting is (60–100) MeV [14]). For each generated event, we then calculate the expected contribution to the full amplitude according to Equation (3) (this amplitude is a function of the kinematic characteristics of a particular event). Finally, we sum over (complex) amplitudes corresponding to the same $M_{(\bar{D}D)^{*+}}$ bin. The resulting Z^+ shapes (equal to $|\sum \mathcal{A}|^2$) for the chains (1) and (2) are shown in Fig. 2; for the latter we plot separately the contributions of different D^* helicities.

The phase of the Z^+ amplitude, $\arg(\mathcal{A}_{Z^+})$, from the reaction (1), which is responsible for the most prominent peak of the $Z(4430)^+$, is presented in Fig. 3 a). Equivalently, we plot the Argand diagram Fig. 3 b) using the same M_{Z^+} binning as the LHCb experiment for direct comparison. The initial phase in our case is arbitrarily set to π , while for the LHCb experiment, it is fixed relative to the reference $B \rightarrow \psi' K$ phase from their 4D-fit. The phase variation around the $Z(4430)^+$ peak arises from the $D_s^{(*)'}$ Breit–Wigner phase variation via the convolution with the angular variables in Equation (3). We note that the higher mass region of $D_s^{(*)'}$ corresponds to lower $Z(4430)^+$ mass, and vice versa. Therefore, in the region around the $Z(4430)^+$ the phase turns out to have opposite behavior relative to the conventional Breit–Wigner definition: it tends to rotate clockwise in the Argand diagram. However, experimentally the direction of amplitude rotation cannot be determined as there is a two-fold ambiguity ($\mathcal{A} \leftrightarrow \bar{\mathcal{A}}$) in the extraction of the Z^+ amplitude from the measured $|\mathcal{A}_{Z^+} + \mathcal{A}_{\text{non-}Z^+}|^2$. Thus, our hypothesis is fully consistent with the LHCb Argand diagram.

To further illustrate that our hypothesis is plausible, we use the LHCb $\psi'\pi^+$ mass spectrum with vetoed $K^*(890)$ and $K_2^*(1430)$

resonances (Fig. 4 from [4]) and perform a toy fit to this spectrum ignoring interference between major $B \rightarrow \psi' K^{(*)}$ and rescattering contributions. This is not a fully correct procedure, we thus use it for illustration only, but having access to the published one-dimensional $M^2_{\psi'\pi^+}$ projections only, we cannot calculate phase-dependent interference effects. We first estimate the remaining contributions from $K^*(890)$, $K_2^*(1430)$ and S -wave three-body phase space, after selecting the $1.0 < M^2_{K^-\pi^+} < 1.8$ GeV² interval, using Figs. 3 a) and b) from [4]. The LHCb data points with these three contributions superimposed (the histogram colors correspond to the LHCb notation) are shown in Fig. 4 a). The spectrum in Fig. 4 b) is obtained after a bin-by-bin subtraction of $K^{(*)}$ and non-resonant three-body decays. We attribute the remaining spectrum to the rescattering contribution and perform a fit to this spectrum with a sum of contributions from the reactions (1) and (2), therefore with five free parameters. We note that all intermediate B decay channels with various $D_s^{(*)'}$ states contribute to Z^+ production coherently with the same universal rescattering amplitude. The fit results are plotted in Fig. 4 b) with the black solid line, and nicely describe all the features observed in data.

We estimate the parameters of the $D_s^{(*)'}$ meson from the fit to the LHCb data. We vary the $D_s^{(*)'}$ mass and width and calculate the confidence level of the fit for each set of values. The result of this exercise is presented in Fig. 5, where the green, magenta and blue contours correspond to 1σ , 2σ and 3σ levels, respectively. The $D_s^{(*)'}$ parameters turn out to be well statistically constrained by the fit: $M = (2614 \pm 4)$ MeV, $\Gamma = (92 \pm 10)$ MeV. However, there is a systematic uncertainty in these values due to the effect of interference with the $K^{(*)}$ background. To estimate this effect we ascribe different phases to the amplitudes of $K^*(890)$, $K_2^*(1430)$ and S -wave three-body phase space and perform another fit to the distribution in Fig. 4 a) with varying $D_s^{(*)'}$ mass and width. Variations of the best fit $D_s^{(*)'}$ parameters depending on

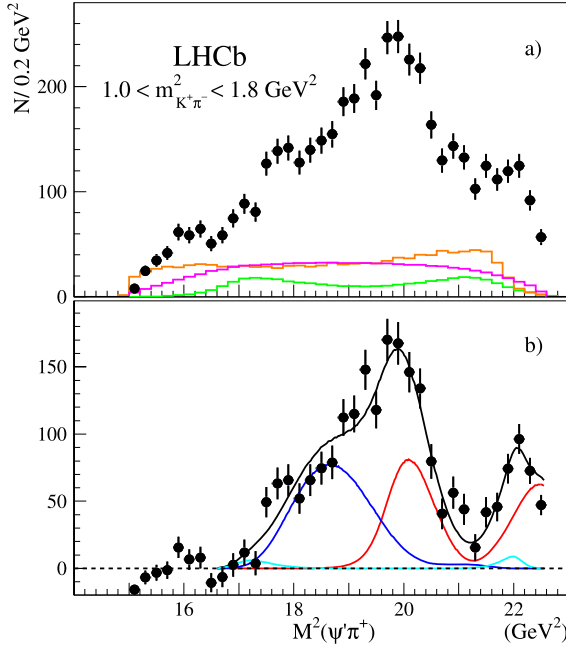


Fig. 4. a) Distribution of $M^2_{\psi'\pi^+}$ in the LHCb data for $1.0 < m^2_{K^+\pi^-} < 1.8 \text{ GeV}^2$ borrowed from [4] (black points); the orange, green and magenta histograms are contributions from $K^*(890)$, $K^*(1430)$ and S-wave three-body phase space, respectively, expected from the LHCb fit. b) Distribution of $M^2_{\psi'\pi^+}$ after incoherent subtraction of contributions from $K^*(890)$, $K^*(1430)$ and non-resonant three-body decays. The black curve represents our fit to the data points. The red, blue and cyan curves represent contributions from the (1) and (2) processes, with $\lambda = 1$ and $\lambda = 0$, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

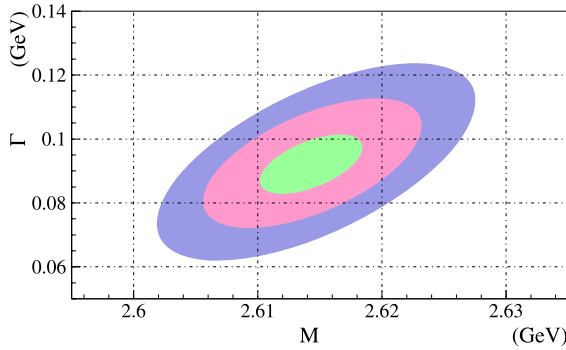


Fig. 5. Mass vs. total width of the D_s^{*-} resonance predicted from its contribution to the rescattering diagram. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the $K^{(*)}$ phases are estimated to be $\pm 10 \text{ MeV}$ for the D_s^{*-} mass and $^{+20}_{-13} \text{ MeV}$ for its width. We thus conclude that, to explain the $Z(4430)^+$ peak, the parameters of the D_s^{*-} meson should be in the interval: $M = (2614 \pm 4^{+20}_{-13}) \text{ MeV}$, $\Gamma = (92 \pm 10 \pm 10) \text{ MeV}$.

Soon after this paper was submitted, another experimental analysis of $\bar{B} \rightarrow J/\psi K^- \pi^+$ by Belle appeared [16]. The existence of the broad structure at $M(J/\psi \pi^+) \sim 4200 \text{ MeV}$ is established in that measurement with high significance and with preferred assignment of the quantum numbers $J^P = 1^+$; strong evidence for a $Z(4430)^+$ signal is also found. The parameters of the two bumps

are consistent between the $J/\psi \pi^+$ and $\psi' \pi^+$ analyzes. However, their relative phases with respect to $B \rightarrow \psi K^{(*)}$ background look different, (e.g. the $Z(4430)^+$ peak is seen as destructively interfering). While in our approach only the strengths of the $(\bar{D}D)^{**}$ rescattering amplitudes, which are real numbers, into $J/\psi \pi^+$ and $\psi' \pi^+$ can be different, this fact can be attributed to the different phases of the interfering $K^{(*)}$ background amplitude under Z^+ 's in these two modes. Indeed, the 3-body phase space is different due to the different J/ψ and ψ' masses. Thus, not only the different helicity regions of the same $K^{(*)}$ contribute to the Z^+ regions in these two modes, but also relative contributions of allowed K^{**} may differ.

A real test of our hypothesis can be achieved with a 4D-fit performed by Belle, BaBar and LHCb for $B \rightarrow \psi' \pi^+ K^-$ decays using amplitudes (3) instead of resonance-like Z^+ 's. Obviously the fitting model with rescattering includes many free parameters: at least three complex amplitudes to describe all possible contributions as well as the as-yet-undetermined parameters of the D_s^{*-} resonance. It is important to fix these amplitudes using a study of $B \rightarrow \bar{D}^{*0} D^+ K^-$ and $B \rightarrow \bar{D}^0 D^{*+} K^-$, which is possible at B-factories or LHCb. However, there is an easier way to check our hypothesis experimentally. The Z^+ -like structures should appear in the distributions of $M_{(D^* \bar{D})^+} \times \cos^2(\theta_{\text{form}})$ in either $B \rightarrow \bar{D}^{*0} D^+ K^-$ or $B \rightarrow \bar{D}^0 D^{*+} K^-$ decays, or in both. The $M_{(D^* \bar{D})^+} \times \cos^2(\theta_{\text{form}})$ is the $(D^* \bar{D})^+$ combination mass spectrum corrected in each bin for the fraction of the D^* transverse component in the $(\bar{D}D)^{**}$ rest frame, and also the 1^+ formation factor $D^2(\theta_{\text{form}}) = \cos^2(\theta_{\text{form}})$.

In summary, we show that $\bar{D}^{*0} D^+ \rightarrow \psi' \pi^+$ rescattering in the decay chain $\bar{B} \rightarrow D_s^{*-} D^+$, $D_s^{*-} \rightarrow \bar{D}^{*0} K^-$ can explain the appearance of an observed peak in the $\psi' \pi^+$ mass spectrum in $\bar{B} \rightarrow \psi' \pi^+ K^-$ decays around $M \sim 4430 \text{ MeV}$ and also correctly describes the quantum numbers and amplitude resonance-like behavior. This approach allows also to describe another peak at $M \sim 4.2 \text{ GeV}$ observed in LHCb data and which has been interpreted as another exotic resonance, as well as a high mass structure at the upper bound of the mass spectrum, which remains still undersaturated by the LHCb fit (with many K^{**} and two $Z(4430)^+$'s included).

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